Int J Life Cycle Assess (2011) 16:878–885
DOI 10.1007/s11367-011-0308-4

CARBON FOOTPRINTING

The climate change implications of offshoring Finnish pulp production to South America

Jáchym Judl · Sirkka Koskela · Tuomas Mattila · Timo Jouttijärvi

Received: 24 February 2011 / Accepted: 26 May 2011 / Published online: 10 June 2011

Abstract
Purpose Offshoring of pulpwood production outside Europe is more and more common, which increases transport distances and also changes production technologies, raw material supply and energy production profiles. In this paper, we aim to compare the life cycle greenhouse gas emissions of pulp production from Finnish boreal hardwood and from South American eucalyptus. Special emphasis was placed on analysing the contribution of transport to overall climate impacts.
Materials and methods A life cycle assessment (LCA) was used as the system modelling tool. The impact assessment was limited to climate change. Finnish and South American industrial data were combined with data from LCA databases in the life cycle inventory (LCI).
Results and discussion Based on the results, offshoring of pulp production would decrease the global greenhouse gas emissions of pulp production itself. However, transport to Europe outweighs the benefit even if transported by energy efficient ships. In this case study, transportation accounted for 27% of the life cycle greenhouse gas emissions of South American pulp shipped to Europe.
Conclusions Outsourcing of biomass production offers opportunities for emission reductions. Such a conclusion may be valid if the distances between biomass production and upgrading processes were relatively short. However, this study reveals that the offshoring of biomass production contributes to a significant growth of transport emissions. The trend of offshoring provides challenges for the implementation of emission trading since the responsibility of countries to transoceanic transport is still unclear.

Keywords Climate change · Eucalyptus · Finland · Offshoring · Pulp · South America · Transport

Responsible editor: Matthias Finkbeiner

J. Judl · S. Koskela (✉) · T. Mattila · T. Jouttijärvi
Finnish Environment Institute SYKE,
Mechelininkatu 34a,
00251 Helsinki, Finland
e-mail: sirkka.koskela@ymparisto.fi

1 Introduction

The pulp industry in Finland has a very long history. Together with the paper industry, it plays an important role in the Finnish economy with 4% of GDP and 12% of export value connected to pulp and paper manufacturing (Seppälä et al. 2009). Currently, chemical pulp is not imported to Finland to a great extent. However, the production of chemical pulp from eucalyptus in South America is becoming increasingly popular, particularly for economic reasons. This may change the import/export ratio in the future. Production of chemical pulp in South America is dominated by Brazil. Brazil is the second biggest producer (and exporter) of chemical pulp in the world (FAO 2010). Production of chemical pulp in South America, as well as in Brazil, has been constantly and rapidly growing (Spinelli et al. 2009; FAO 2010).

Globally, transportation is increasing as a result of offshoring the production of commodities. It is a result of relocating primary production further from upgrading processes. A considerable part of the environmental impacts caused by European consumption is currently occurring outside European boundaries (Peters and Hertwich 2008). For example, the tendency of moving pulp production towards fast-growing biomass reserves increases the offshoring trend.

Offshoring of European pulp production may potentially have an influence on climate change impacts. Therefore,

the aim of this study was first to compare the climate change impacts of current pulp production from boreal hardwood with production from eucalyptus. Secondly, we assessed what the climate impacts would be if a larger proportion of annual pulp demand in Finland was produced in South America and transported to Finland. The production volumes represent the year 2008. We put special emphasis on analysis of the logistics system in pulp production and distribution. We analysed the transportation patterns of pulp production in detail beginning with logging and ending with the shipping of pulp to a paper mill situated in Finland. For emission-intensive products, such as food, the share of life cycle emissions from transportation is usually minor (Weber and Matthews 2008), but for heavy bulk goods such as wood products, it may have some influence on the overall result.

If chemical pulp production gradually moved from Finland to South America, several future scenarios are conceivable. In this paper, we analysed a scenario in which an increasing amount of pulp is produced in South America and then shipped to Finland, where the paper production would remain situated.

The moving of both pulp and paper production to South America, where paper would be imported to Europe, could be another possible scenario. In the last but not least likely scenario, paper production would also move outside of Finland but to China or India rather than South America. Finnish companies are currently investing in large state-of-the-art paper mills in China from where the paper could be imported to Finland and the rest of Europe.

To predict the future is always challenging, but all of these alternatives will more or less increase international transportation. Of the scenarios outlined above, only the first was analysed, but it is appropriate to acknowledge them all.

Our paper aims to answer the following questions:

- What was the cradle-to-gate impact of average Finnish and South American chemical pulp production on climate change in 2008?
- How significant would the impact of long-distance transoceanic transportation be on climate change in a scenario where South American pulp production and imports to Finland increase as Finnish pulp production decreases proportionally?

1.1 Finnish pulp industry

The Finnish pulp industry in 2008 was the sixth biggest producer of chemical pulp in the world with production exceeding 7 million ADt (air-dry tonne) of chemical pulp (FAO 2010). Europe's production in the same year accounted for 32.5 million ADt (FAO 2010). Therefore, the Finnish share of the European production was 22%. The world's production in 2008 was 130 million ADt (FAO 2010) with Finland's share of the world's production representing 5.5%.

Many other businesses and subcontractors are directly or indirectly connected to the pulp (and paper) industry in Finland. Pulp (and paper) mills are often core plants in industrial parks and zones (Pakarinen et al. 2010). This is mainly due to their capacity to produce surplus energy and heat which can be used by other businesses with low losses. Bio-based residues can also be used by other businesses, e.g. bark or sawdust.

The raw material for pulp production is wood. In Finland, the pulp industry uses both softwood and hardwood (Metso 2010). In our analysis, we focus on hardwood chemical pulp only, particularly made from domestically supplied birch (*Betula pendula*, *Betula pubescens*). The Finnish pulp industry not only is supplied by domestically produced wood but also imports from other countries. The main long-term partner in industrial roundwood imports is Russia.

In recent years, the Finnish pulp industry has been undergoing some structural changes. Some older pulp mills have been shut down in line with corporate strategy and economic considerations. Finnish forest companies have invested in pulp mills in Brazil and Uruguay, either individually or jointly with South American companies, and other mills are in the pipeline. The mills utilize the latest technology and are designed for a very high level of environmental protection. Domestic chemical pulp production in Finland remains at a high level, although in the future it is likely that more and more existing pulp production will be offshored.

1.2 South American pulp industry

According to FAO statistics (FAO 2010), production of South American chemical pulp doubled in the 10 years between 1998 and 2008, exceeding 18 million ADt of chemical pulp in 2008, and accounting for 14.2% of the world's production volumes. Over 55% of the production was exported.

Brazilian chemical pulp production followed the trend of South American chemical pulp production. The production exceeded 12 million ADt of chemical pulp in 2008, which accounted for over 65% of the South American production of chemical pulp. Almost 60% of the production was exported. In 2008, Brazil was the second biggest producer of chemical pulp in the world.

USA was the biggest pulp producer in 2008. Its production was more than three times larger than the Brazilian one (approximately 45 million ADt of chemical pulp; 35% of the world's production).

Chemical pulp in South America is produced almost exclusively from hardwood of eucalyptus (*Eucalyptus globulus*, *Eucalyptus grandis*). Eucalyptus results in a more economical production of pulp since it grows fast, it is easy to harvest, it has advantageous fibre characteristics (fibre is short and lignin content is low) and it is easier to bleach. Eucalyptus grown in tropical areas is ready to be harvested for the pulp making process after just 7 years of growth (Stape et al. 2004), whereas birch needs more than twice as much time to grow into a sufficient volume. Eucalyptus plantations are easier to harvest than boreal forest as rationalized plantation grid structures make utilizing machinery possible to a greater extent. This contributes to faster production of wood, higher fibre yields and lower costs.

In contrast to Finland, where the produced pulp is utilized by local Finnish paper production, South American pulp is mostly exported rather than upgraded locally.

2 Materials and methods

2.1 System boundaries

Our scenario includes wood harvesting, production of chemical pulp and transportation (Fig. 1). In the scenario, two pathways were used—Finnish and South American—to fulfil the pulp demand of the Finnish paper production, which is, however, set outside the product system. At the beginning, only the Finnish pulp (100%) fulfilled the demand of the paper mill, and gradually, it was decreased by 20% at a time until the share of Finnish pulp was 0%. Every unit process also requires raw materials, chemicals and energy, which are included in the product systems.

The scenario analysis was constructed as a cradle-to-gate life cycle assessment (LCA), only focusing on the climate change impact category. Flows of raw materials and pulp were linked to transport processes. All the processes, which are not directly linked to the pulp production, were excluded in order to keep the dimensions of the system feasible. Cut-offs were especially applied to all the emission flows that do not affect climate change. Only main greenhouse gas emissions, i.e. carbon dioxide (CO_2), methane (CH_4) and dinitrogen monoxide (N_2O), were the selected emission flows which were inventoried.

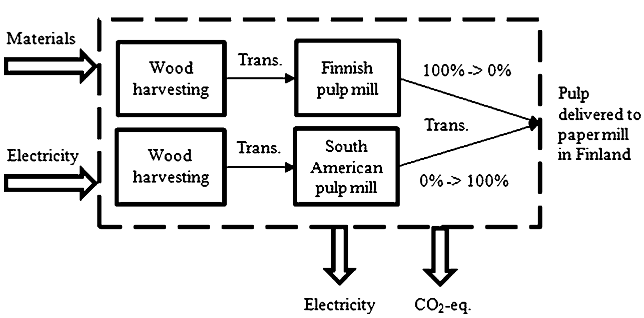

Fig. 1 The boundaries of the product systems (*dashed line*). *Thick arrows* represent the system's inputs and outputs. The amount of Finnish pulp was decreased from 100% to 0%, and South American pulp was increased from 0% to 100% respectively

Transportation was modelled using the well-to-wheel approach, i.e. infrastructure emissions were omitted. This cut-off was made to limit the extent of uncertainty in describing the road network in South America. Only emissions from fuel combustion and the manufacture of vehicles were therefore included.

The functional unit was defined as *an ADt of chemical pulp delivered to the paper mill in Finland*. It was therefore assumed that only pulp production would be relocated, and paper mills would remain in Finland.

The analysis was constructed as a comparison of current state-of-the-art current pulp production technologies in South America with pulp production in Finland. An attributional LCA (ILCD 2010) was used for modelling. However, the possible direct effects of increasing eucalyptus demand and decreasing boreal pulpwood demand on society and the environment were not included due to the focus of the analysis on production technology and transportation. This limits the use of the results for decision making, but allows an identification of the main differences between the two production systems and the potential increase of transport emissions.

One of the main environmental impacts of transport is considered to be its impact on climate change (EEA 2010). Therefore, the analysis was limited to a quantification of climate change impacts.

2.2 Data collection

Volumes of the main raw material (wood) and process chemicals in Finnish pulp production are based on data obtained from Finnish mills and reference documents (Vasara et al. 2001). For South American mills, expert judgments were also used. Average electricity production data for Brazil and Finland were obtained from the Ecoinvent database v.2.2 (Ecoinvent 2010).

The following transport processes were studied in detail: the transport of logs from the logging site to a pulp mill, the transport of air-dry pulp from the pulp mill to a paper mill and the transport of process chemicals from the manufacturer to the pulp mill. Wood transport distances and the delivery distances of chemicals from companies were acquired, both for Finland and South America. The transport distances of pulp transport were calculated based on information obtained from sustainability reports for major pulp mills located in South America. The findings of Dahlbo et al. (2005) and the Ecoinvent database (Ecoinvent

2010) were used as a source of inventory emission data for transportation vehicles and vessels.

2.3 Calculation method

The matrix-based life cycle inventory method implemented in a spreadsheet was used to construct the product systems. The method was first introduced by Heijungs (1994) and further described by Suh and Huppes (2005). It operates with a set of linear equations which describe the analysed system. This approach allowed us to model the analysed system in detail. The method is also well suited for modelling various transport solutions.

In order to calculate the climate change impacts of the system, we focused on an inventory of three major greenhouse gas (GHG) emissions. The flows of fossil carbon dioxide (CO_2), methane (CH_4) and dinitrogen monoxide (N_2O) were quantified. Their characterization factors for the impact category *climate change* are 1, 25 and 298, respectively (IPCC 2007). Biogenic GHG emissions were not taken into account.

The life cycle of chemical pulp was divided into the following life cycle stages:

- felling;
- production of chemicals (including make-up chemicals);
- production of chemical pulp;
- transport (including logging as well as supply of chemicals); and
- production of electricity.

The end-of-life stage of paper was excluded from the calculation.

2.4 Life cycle inventory of pulp mills

Pulp mills can generally be classified as integrated and non-integrated. The integrated pulp mills are located within larger industrial units, often interconnected with other industrial processes (most commonly with paper production, power plant or heat-generating plant). Non-integrated pulp mills, on the contrary, are not connected to other industrial processes (except heat or power generation). Finnish pulp mills do not use exactly the same production technology. Typically, several pulps are in production, with chemical pulp in the forefront. Assessing average climate change impacts for the Finnish pulp was therefore rather challenging task.

The focus of this study was on non-integrated pulp mills. The principle and technology used in South American chemical pulp mills is basically the same as in non-integrated pulp mills in Finland. However, there are minor differences between them. The main difference is, of course, the raw material which is eucalyptus roundwood. Due to the physicochemical properties of eucalyptus, the delignification process of the wood is easier, and therefore, less organic residues are generated. Higher yields in eucalyptus cooking will result in less energy out from the recovery process than in the case of birch cooking. On the other hand, lower production of bio-waste results in a lower potential for generating power or heat.

The pulp process requires a lot of chemicals (Table 1). It was recorded that South American mills use the same chemicals with approximately the same volumes. However, the use of bleaching chemicals was reported to be 10% lower in South America than in Finland (easier delignification of eucalyptus).

Replacing chlorine-based bleaching chemicals with hydrogen peroxide, oxygen or ozone improved environmental performance of pulp mills and enabled a full recovery of process chemicals, e.g. burning black liquor (Rousu et al. 2002).

2.5 Crediting of surplus electricity

In addition to the pulp product, the process of pulp making generates surplus energy from the combustion of black liquor. The black liquor (spent cooking liquor) contains inorganic cooking chemicals and lignin. The content of lignin in wood is approximately 50% (less than 50% in eucalyptus wood). The black liquor is commonly burned during the recovery process. The aim is to recover cooking chemicals and also energy (Saviharju 1993; Soares et al. 2001). We assumed that the model state-of-the-art pulp mills produce enough electricity for their own operations by burning black liquor (Fibria 2010) and biological residues, like bark and sawdust (Sokka et al. 2011). According to the LCA principals, surplus electricity was credited to pulp production by using system expansion and assuming that average grid electricity production was replaced (Pakarinen et al. 2010; Fibria 2010).

Table 1 Inventory of the main inputs of chemical pulp production in Finland and in South America, per 1 ADt (Koponen 2010, Keskisaari 2010, Vasara et al. 2001)

		Finland	South America
Chemicals (kg/ADt)	NaOH	35	35
	$NaClO_3$	39	35
	NaCl	21	19
	O_2	35	32
	H_2O_2	8	7
	H_2SO_4	20	20
	CaO	10	10
Wood (m^3/ADt)		5.2	4

In Finland, the amount of electricity supplied to the grid was estimated to be 12% of the pulp mill's total electricity production. In South America, it was assumed that less surplus electricity is available due to the lower lignin content of eucalyptus wood and the lower generation of biological residues (i.e. 10% of the total electricity production is sold to the grid) (Keskisaari 2010). This applies to a pulp mill where chlorate is not made on-site but is produced elsewhere. If chlorate was produced on-site, the surplus electricity would be consumed during the process.

2.6 Transportation

Logging in Finland often takes place in large remote areas. This results in longer transport distances of wood. The average domestic logging distance was reported to be 200 km (Keskisaari 2010). The logistics network of wood supply in South America is different from the Scandinavian one. In general, distances for wood supply are shorter in South America than in Finland due to a different type of forestry known as plantation forestry. Eucalyptus plantations are planted relatively close to pulp mills. The average transportation distance from a plantation to a pulp mill was assumed, based on industrial data, to be 75 km on average.

In Finland, wood is transported by road, rail and water. For the purpose of our analysis into only road transport was taken into account due to the availability of data and to avoid underestimation of emissions. The emission intensity of a logging truck was sourced from Dahlbo et al. (2005). For South American logging, the emission intensity was increased by 25% based on a presumption that the truck fleet in South America would have a lower environmental performance (Pinheiro 2003).

In the case of South America, chemical pulp is transported from the pulp mill by trucks to a river terminal, transferred on river barges and transported to a major port. There the pulp bales are transferred on transoceanic freight ships. The logistics system was modelled on the basis of a real pulp mill in South America.

3 Results and discussion

3.1 Climate change impacts of average pulp production

We identified the manufacturing of process chemicals as the life cycle stage with the highest potential impacts on climate change (Table 2; Fig. 2). The second most important life cycle stage is the production of pulp itself. Cradle-to-gate global warming potentials of South American eucalyptus pulp and Finnish hardwood pulp were 422 kg CO_2-eq./ADt and 441 kg CO_2-eq./ADt, respectively. Harvesting and transportation have a less significant impact on climate change compared to the production of chemicals and pulp. Compared to Finnish production, South American production has several benefits. The emissions of all processing stages are lower than in Finland. Felling is less energy intensive, transport distances are shorter, fewer chemicals are needed and the emissions of pulp production are lower. Even though less heat and electricity are generated by by-products, the overall balance favours production from eucalyptus. However, transportation of pulp from South America to Finland changes the overall picture. Emissions from transoceanic freight transport are almost as high as the production of pulp. Although the specific emission factors (per tonne-kilometre) for ocean vessels are lower than those of other transport vehicles, the distance between South America and Finland (over 11,000 km) makes the difference. The transport of eucalyptus pulp from South America to Finland would increase its GHG emissions by over 31%.

Table 2 Climate change impacts of 1 ADt of chemical pulp produced in Finland, produced in South America and produced in South America and imported to Finland

Climate change impact (kg CO_2-eq.)	Finnish pulp	South American pulp	South American pulp imported to Finland
Felling	40	29	29
Chemicals	244	232	232
Production	172	154	154
Transport	34	18	18
Transoceanic transport	0	0	132
Electricity	−48	−12	−12
Total	441	422	554

The rows represent different life cycle stages in pulp production

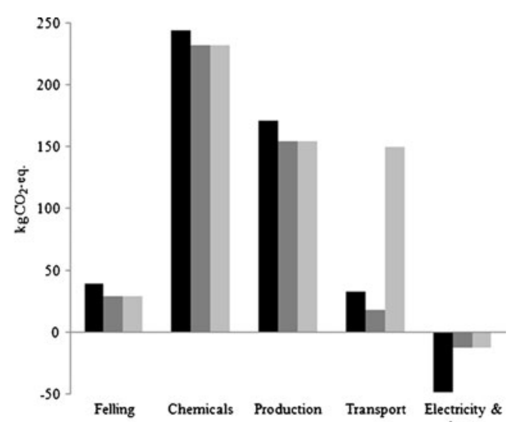

Fig. 2 Climate change impacts of producing 1 ADt of chemical pulp, for each life-cycle stage (in kg CO_2-eq.). *Black columns* represent Finnish pulp, *grey columns* represent South American pulp and *light grey columns* represent South American pulp imported to Finland

3.1.1 Climate change impacts of transportation

Operational GHG emissions of the different means of freight transport per tonne-kilometre (tkm) differ. The lowest GHG emissions per 1 tkm are emitted by ocean-going vessels, followed by heavy duty trucks, river barges, logging trucks in Finland (Ecoinvent 2010; KCL 2008; Dahlbo et al. 2005) and logging trucks in South America. GHG emissions of ocean-going vessels are approximately 25% of the heavy duty truck.

Overall, the contribution of transportation to climate impacts was considerably higher than what could be expected from other studies (Weber and Matthews 2008). For the pulp produced in Finland, it accounted for 8% of the total climate change impacts, for pulp shipped from South America, it accounted for 27%. If the share of offshored pulp increases, the emissions from transoceanic freight transport will grow. This poses a problem for climate mitigation since currently no country takes responsibility for international freight transport. In this case, offshoring would be seen as a decrease in emissions for both Finland and Brazil, but the actual global GHG emissions would increase. Therefore, it is important to focus research activities on the quantification of maritime emissions (Schrooten et al. 2009).

Nevertheless, the first measures to address the issue of transoceanic freight transport have already been taken. In the EU, a new emission-limiting policy for sea transport has recently come into action (DG Environment 2011).

3.1.2 Future scenario

If all chemical pulp production was relocated to South America the overall impact on climate change from felling, manufacturing of chemicals and pulp production would diminish by less than 1%. The credit from electricity production would decrease by 75.5%, and at the same time, transportation emissions would increase by almost 350% (Table 3). The climate change impacts would increase by 25% if pulp was imported from South America to Finland (Fig. 3).

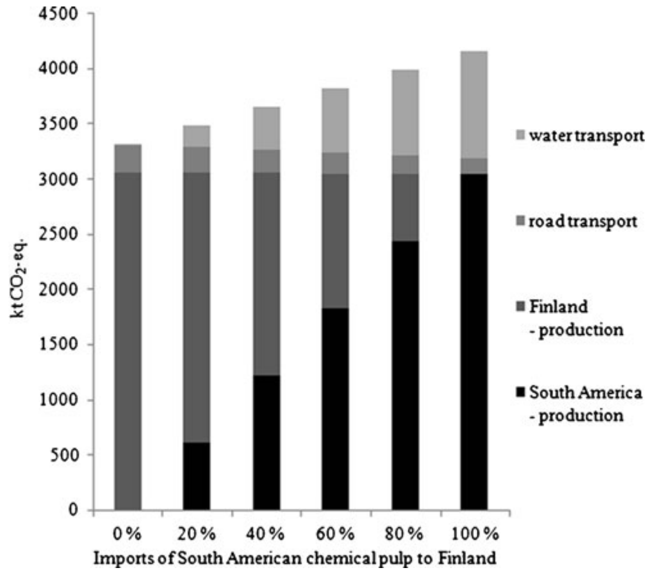

Fig. 3 Shift in climate change impacts of annual chemical pulp production in 2008 for pulp upgrading in Finland if Finnish pulp is gradually substituted by South American pulp

3.2 Limitations of the approach

The study was constructed as a comparison of two existing systems based on average data. Using the prevailing terminology of LCA, the comparison was an attributional accounting situation for two alternative production systems (ILCD 2010). Therefore, the results cannot be used to predict what would happen if the trend would continue. For example, what would happen to the boreal forest biomass, which is no longer used for pulp making? Would it be used for fuel or left standing as carbon storage? Would the increased pressure on tropical forests increase deforestation? Answering these kinds of questions would require a consequential LCA approach (Ekvall and Weidema 2004) and was outside the scope of this study.

Many features of pulp production, such as the difference between integrated and non-integrated pulp mills among others, could not be included in this study. The case study focused on non-integrated pulp mills only.

Table 3 Climate change impacts of annual chemical pulp production in 2008, per life cycle stage and level of import

Climate change impact (kt CO_2-eq.)		Percentages of South American chemical pulp imports to Finland					
		0%	20%	40%	60%	80%	100%
Life-cycle stages	Felling	299	283	267	252	236	220
	Chemicals	1,838	1,820	1,802	1,784	1,766	1,748
	Production	1,292	1,266	1,240	1,215	1,189	1,161
	Transport	253	429	605	781	957	1,133
	Electricity	−364	−309	−254	−199	−144	−89
	Total	3,318	3,489	3,661	3,832	4,003	4,175

Values in kt of CO_2-eq.

The acquired data, especially concerning logistics and Finnish pulp production, were in general of good quality. Some uncertainty is associated with the process specific data for South American pulp mills. However, to avoid uncertainty in primary data, industrial experts familiar with both South American and Finnish pulp production were interviewed.

Using average LCI data has an effect on representativeness of results. In our study, generic inventory data of chemical manufacturing were used in the calculation since the focus was primarily on transport and secondarily on pulp manufacturing. Manufacturing of chemicals is energy intensive, and therefore, the energy production profile plays a significant role in their inventory data. If the focus of the study had been primarily on pulp production, specific inventory data for chemicals, or sensitivity analysis, would have been required.

4 Conclusions

The Finnish pulp and paper industry is facing many challenges in the forthcoming years. Real future trends in pulp and paper manufacturing are still unknown. Relocation of pulp production near to profitable raw material is naturally very tempting. The offshoring process includes both advantages and disadvantages in terms of climate change impacts, of which the most significant are related to the various impacts of eucalyptus plantations and increasing international transport, particularly transoceanic transport. The main environmental impact from ship transport is greenhouse gas emissions.

The comparative results of Finnish and South American pulp production indicate that impacts on climate change from chemical pulp manufacturing in Finland are potentially slightly higher than similar activities in South America. The main reasons are the recently built South American pulp mills utilizing the newest technology and the superior raw material harvested closer to production. On these grounds, we could conclude that the relocation of pulp production to tropical regions has the potential to decrease the greenhouse gas emissions of pulp manufacture. However, LCA proved that impacts on climate change from the transport of South American chemical pulp offsets the benefits related to the production of pulp in South America. Sea transport is the *key contributor* to the increased climate impacts.

Although the business decisions are still to a great deal based on economic issues, the environmental impacts are also a concern of society and companies. This study utilized the concise attributional LCA methodology for a future overview, but real decision making needs a consequential LCA considering many other impacts then just climate change.

Based on this study, we can, however, conclude that long transport distances play a significant role in the overall assessment. As long as oceanic transport is cheap relative to production costs, transoceanic transport of bulk commodities such as pulp remains a viable alternative. More research on improving the global logistics of bulk commodities is needed to mitigate the risks of increasing transoceanic transport emissions.

Acknowledgements This study was a part of the LOGMAN project, funded by the European Commission-DG MOVE, 7th Framework Programme, Grant Agreement Number 233691.

References

Dahlbo H, Laukka J, Myllymaa T, Koskela S, Tenhunen J, Seppälä J, Jouttijärvi T, Melanen M (2005) Waste management options for discarded newspaper in the Helsinki Metropolitan Area—life-cycle assessment report. The Finnish Environment 752

DG Environment (2011) Transport & environment—EU policy on ship emissions. http://ec.europa.eu/environment/air/transport/pdf/sulphur_standard_shipping.pdf. Accessed 11 Jan 2011

Ecoinvent (2010) Ecoinvent database v2.2. Swiss Centre for Life Cycle Inventories

EEA Report (2010) Towards a resource-efficient transport system, TERM 2009: indicators tracking transport and environment in the European Union, European Environment Agency

Ekvall T, Weidema BP (2004) System boundaries and input data in consequential life cycle inventory analysis. Int J Life Cycle Assess 9(3):161–171

FAO (2010) FAOSTAT—forestry statistic http://faostat.fao.org/ Accessed 20 Dec 2010

Fibria (2010) FIBRIA—Três Lagoas mill. http://www.fibria.com.br/web/en/negocios/celulose/tres.htm Accessed 20 Dec 2010

Heijungs R (1994) A generic method for the identification of options for cleaner products. Ecol Econ 10(1):69–81

ILCD (2010) General guide for Life Cycle Assessment (LCA)—detailed guidance. Joint Research Centre, Institute for Environment and Sustainability, Ispra

IPCC (2007) Climate change 2007: the physical science basis, Cambridge University Press

KCL (2008) KCL-ECO 4.1 database, VTT Technical Research Centre Finland

Keskisaari, Tiina. Stora Enso Oyj; personal communication, March 2010

Koponen, Raili. Metsä-Botnia Oyj; personal communication, March 2010

Metso (2010) Chemical pulp production. http://www.metso.com/corporation/info_eng.nsf/WebWID/WTB-060629-2256F-5A4FA Accessed 11 Jan 2011

Pakarinen S, Mattila T, Melanen M, Nissinen A, Sokka L (2010) Sustainability and industrial symbiosis—the evolution of a Finnish forest industry complex. Resour Conservat Recycl 54 (12):1393–1404

Peters GP, Hertwich EG (2008) CO_2 embodied in international trade with implications for global climate policy. Environ Sci Technol 42(5):1401–1407

Pinheiro FC (2003) Program for control of air pollution from mobile sources (PROCONVE) analysis—part I, introduction. http://www.epa.gov/ies/pdf/brazil/ies_proconve1_intro.pdf. Accessed 21 Dec 2010

Rousu P, Rousu P, Anttila J (2002) Sustainable pulp production from agricultural waste. Resour Conservat Recycl 35(1–2):85–103

Saviharju K (1993) Black-liquor gasification: results from laboratory research and rig tests. Bioresour Technol 46(1–2):145–151

Schrooten L, De Vlieger I, Panis LI, Chiffi C, Pastori E (2009) Emissions of maritime transport: a European reference system. Sci Total Environ 408(2):318–323

Seppälä J, Mäenpää I, Koskela S, Mattila T, Nissinen A, Katajajuuri J, Härmä T, Korhonen M, Saarinen M, Virtanen Y (2009) Estimating the environmental impacts of the material flows of the Finnish national economy; (in Finnish); Finnish Environment 20/2009

Soares JB, Szklo AS, Tolmasquim MT (2001) Incentive policies for natural gas-fired cogeneration in Brazil's industrial sector—case studies: chemical plant and pulp mill. Energ Pol 29(3):205–215

Sokka L, Pakarinen S, Melanen M (2011) Industrial symbiosis contributing to more sustainable energy use—an example from the forest industry in Kymenlaakso, Finland. J Clean Prod 19 (4):285–293

Spinelli R, Ward SM, Owende PM (2009) A harvest and transport cost model for *Eucalyptus spp.* fast-growing short rotation plantations. Biomass Bioenerg 33(9):1265–1270

Stape JL, Binkley D, Ryan MG (2004) Eucalyptus production and the supply, use and efficiency of use of water, light and nitrogen across a geographic gradient in Brazil. Forest Ecol Manag 193 (1–2):17–31

Suh S, Huppes G (2005) Methods for life cycle inventory of a product. J Clean Prod 13(7):687–697

Vasara V, Jäppinen H, Lobbas P (2001) A strategic concept for best available techniques in the forest industry, Finnish Environment 425

Weber CL, Matthews HS (2008) Food-miles and the relative climate impacts of food choices in the United States. Environ Sci Technol 42(10):3508–3513